N92-22372

LABORATORY STUDY OF THE TEMPORAL EVOLUTION OF THE CURRENT–VOLTAGE CHARACTERISTIC OF A PROBE IN THE WAKE OF AN OBJECT IMMERSED IN A PULSED FLOWING PLASMA

S. Meassick and C. Chan
Department of Electrical and Computer Engineering
Northeastern University, Boston, MA 02115

ABSTRACT

Measurements of the current voltage characteristics of a Langmuir probe in the near wake of a disk immersed in a pulsed flowing plasma have been made. A 1 cm diameter biasable sphere was placed in the ion-free near wake region of a 10 cm diameter disk immersed in a Mach 8 pulsed flowing plasma. The current–voltage characteristic of the sphere was observed as a function of time as the sphere bias was scanned from $-5000\ V$ to $+1000\ V$. The collected current is found to be monotonically increasing with increasing positive bias voltage but exhibits a threshold voltage for current collection as the bias voltage becomes more negative. Potential measurements in the wake region were made for a sphere bias voltages below, at, and above the current collection threshold for a number of times during the wake formation period. The time evolution of the potential profile is shown to change as the sheath around the biased sphere is established. Predictions from the particle trajectory code SIMION are compared with data, showing excellent agreement in the prediction of the current collection threshold.

INTRODUCTION

The issue of current collection by a charged object in the wake of another, usually larger, object is becoming more important as larger platforms, especially in near polar orbits are contemplated. With structures that are many thousands of Debye lengths in size the plasma density in the near wake region will be reduced to a small fraction of the ambient plasma density. Objects in this wake region will not draw any appreciable current until the potential on the object is sufficient to draw charged particles across the depleted plasma region from the plasma flowing around the object creating the wake. In addition, in the case of ions, there may also be an angular momentum barrier to overcome for ion current collection.

Due to their importance, the study of plasma wakes has long been an area of interest in space physics. Numerous investigators, including *Samir et.al.* [1979, 1981, and 1986] and *Medved* [1969], have investigated problems of the environment of a small satellite in the ionosphere. The wake region of large objects such as the space shuttle has been investigated by *Riatt et.al.* [1987] and *Murphy et.al.* [1986]. In fact in 1985 the *Plasma Diagnostics Package* was flown as part of the Spacelab-2 mission. This free flying satellite was designed to make comprehensive measurements of the plasma density, temperature and turbulence in the near, mid and far wake of the space shuttle.

The problem of current collection in the wake of an object in space has received considerably less attention. But for some theoretical predictions of a threshold voltage for ion current collection and some laboratory simulations (*Chan et.al.* [1989]) that have verified these predictions, very little work has been done in this area. In order to gain a fuller understanding of the problem of a Langmuir probe in the wake of a conducting body (ie. current collection in the wake of another body) we have done a series of laboratory experiments to study the dynamics of the current-voltage characteristics of a biased Langmuir probe placed in the wake of a conducting body. We have made comprehensive measurements of the current collected by and the plasma potential around a Langmuir probe as the wake region is established.

DESCRIPTION OF EXPERIMENT

The pulsed plasma wind experiment (PPWE) [*Measssick et.al.*, 1991; *Chan et.al.*, 1984; *Morgan et.al.*, 1987] that we have developed to study the dynamics of current collection of a Langmuir probe in the wake of another body in low earth orbit (LEO) is shown schematically in figure 1. This device consists of a source region and a flowing plasma region. The source region is 30 cm in length and 50 cm in diameter while the flowing plasma region is 70 cm in length and also 50 cm in diameter. The plasma is created in the source region via a multidipole discharge and is allowed to flow into the flowing plasma region where the object creating the wake structure and the Langmuir probe are

present. The energy of the ions is adjustable through a bias voltage applied to the source region. The dynamics of the current collection problem are studied by pulsing the plasma into the flowing plasma region and measuring the response of the current-voltage characteristic of a Langmuir probe and the plasma potential profiles around it.

This experimental arrangement has allowed us to create a pulsed flowing plasma with a variable ion Mach number in the range of 1 to 10. For the experiments reported on in this paper, the plasma flowing into the flowing plasma region has a maximum density of 1×10^8 cm^3 and a parallel and perpendicular ion temperature of 4 eV and 2 eV respectively. The electrons have a perpendicular temperature of 2 eV and a parallel energy of approximately 6 eV. The plasma expanding into the flowing plasma region is not initially in contact with either the side or end walls of the chamber and does not reach the end or side walls of the chamber for approximately 120 μs after the plasma is pulsed into the flowing plasma region.
In order to measure the dynamics of current collection of a Langmuir probe in the wake of a larger object a grounded 10 cm diameter conducting disk was placed 10 cm downstream of the source region. This disk was grounded in order to have constant boundary conditions and eliminate the large floating potential fluctuations of a disk placed in a pulsed flowing plasma as seen by ***Morgan et.al.*** [1989]. A spherical Langmuir probe, 1 cm diameter, was placed on axis 5 cm downstream of the disk. The Langmuir probe was biasable through an external power supply from +5000 to -5000 V. For these experiments, the base pressure of the device was approximately 5×10^{-7} Torr while the operating pressure during measurements was 5×10^{-5} Torr of Argon.

Collecting and emitting Langmuir probes were utilized to monitor the plasma parameters in the source and flowing plasma regions. Collecting Langmuir probes, consisting of 0.64 cm diameter disks were used to monitor the plasma density and the electron temperature in the source region. Retarding Potential Analyzers (RPA) were used to measure the ion temperature in the source region and to measure the ion and electron distributions in the flowing plasma regions. Emissive Langmuir probes were used to measure the plasma potential. These probes were operated in the limit of zero emission utilizing the inflection-point method (*Smith et.al.* [1979]) in order to minimize the perturbation of the plasma. All probes were constructed to have a maximum time resolution of 1 μs and were scannable to cover the source and flowing plasma regions.

Data from all of the probes were sampled with a boxcar averager that was triggered when the plasma began flowing into the flowing plasma region. This allosed sampling of the data at the times of interest and reduction of noise.

EXPERIMENTAL RESULTS

Measurements of the current collected by the Langmuir probe were made over a bias voltage range of +500 to -5000 V. Figure 2a shows the amount of current collected by the probe as a function probe bias voltage at 100 μs after the start of the plasma pulse. At this time the wake region is already well established and has reached steady-state conditions. It is evident that for positive bias voltages, there is a rapid increase in the current, reaching a saturation current of somewhat greater than 1 mA at a bias voltage of approximately 100 V. For negative bias voltages applied to the Langmuir probe no current is collected until the bias voltage reached approximately -2.2 kV after which ion current is collected.

Figure 2b shows the current collected by the Langmuir probe as a function of time. It is evident that the threshold voltage for ion current collection increases rapidly at early times. At late times (100 μs) the threshold for ion collection is approximately -2.2 kV and increases to approximately -5 kV at very early times (30 μs) as the wake is just being established.

In order to gain an understanding of the temporal evolution of the voltage-current characteristic of the Langmuir probe, simultaneous measurements of the plasma potential throughout the near and mid wake region were made. These potentials measurements were made with Langmuir probe bias potentials of -2000, and -3000 V. These bias voltages were chosen to gain an understanding of the current collection threshold characteristics. The dynamics of the potential profiles were studied by taking measurements of the plasma potential during the formation of the wake from the time that the flowing plasma just arrives in the wake region (30 μs) until a steady state has been achieved (100 μs).

Figure 3a-d shows the temporal evolution of the potential profiles just below the current collection threshold at -2000 V. From part a of this figure it is evident that the negative potential profile extends far past the disk radius at 30 μs (the -10 V equal potential profile extends out to a radius of 8 cm). There are negative potential "wings" that extend upstream of the disk. At 40 μs, shown in part b of this figure the -10 V equal potential profile has decreased in radius so that it now only extents slightly past the disk radius. In addition the axial extent of the -10 V equal potential profile downstream of the Langmuir probe has decreased from 12 to 8 cm and the negative potential "wings" have disappeared. In part c of the figure, at 80 μs, the -10 V equal potential profile extends to a radius of less than that of the disk, indicating that the large electric field region is now confined to small radii. It is also evident that at this time that an enhanced potential

region is forming on axis downstream of the sphere (for axial distances greater than 10 cm). Figure 3d shows that for late times all of the negative potential regions are at radii less than the disk radius. In addition, the enhanced potential region first seen in at 80 μs is now much more pronounced.

The temporal evolution of the plasma potential for a Langmuir probe bias voltage above the current collection threshold voltage is shown in figure 4a-d. With a Langmuir probe bias potential of -3000 V the sheath region extends far from the probe. Even at 100 μs the -10 V equal potential contour is at a radius of 5 cm, the same as the radius of the disk creating the wake. In addition, the on axis potential enhancement seen with a Langmuir probe bias of -2000 V is no longer evident. The "wings" that only extended upstream of the disk at 30 μs for lower probe bias voltages now are also present at 40 μs.

DISCUSSION

The two most significant features of the current-voltage characteristic of a biased Langmuir probe placed in the wake are that there is a threshold voltage for ion current collection and that this threshold voltage is a strong function of time during the formative stages of the wake.

The threshold voltage for current collection has been seen in steady state experiments performed by *Chan et.al.* [1989]. In those experiments a 10 cm diameter disk was placed in a 1.7 by 1.7 m vacuum chamber in order to eliminate wall effects. The threshold voltage for ion current collection with a 1 cm diameter Langmuir probe 5 cm downstream of the disk is -2200 V, almost identical to the threshold voltage reported in this experiments for late times. The measured potential profiles are nearly identical to the ones presented in this paper for late times.

In order to gain some insight into the temporal variations of the current collection threshold we have utilized the charged particle trajectory code SIMION (*Dahl and Delmor* [1988]). This is a two dimensional Poisson solver that solves for space potentials, not including space charge effects, given boundary conditions and allows the tracking of charged particle trajectories. In order to utilize this code the measured potential profiles were entered and particle trajectories were followed.

Figure 5a,b shows the trajectories for ions with Langmuir probe bias potentials of -2000, and -3000 V respectively. The angle of the ion trajectories is due to the finite perpendicular energy of the ions. From these figures it is evident that ions are only collected by the sphere for bias potentials greater than -3000 V. For bias potentials smaller than -3000 V the ions are deflected by the potential gradients with their trajectories crossing 10 to 15 cm downstream of the disk. This is at the same axial location where the is an enhancement of the plasma potential.

Figure 6a-c shows the ion trajectories for the Langmuir probe biased at -3000 V at 40, 80, and 100 μs respectively. From these figures it is evident that for early times, where the sheath region extends far from the Langmuir probe, the ion orbits do not hit the probe. As the sheath region shrinks the ions come closer to the probe until their orbits intersect the probe and are collected. In addition, at earlier times there is very little focusing of the ion trajectories downstream of the probe (there is no enhanced potential region downstream for early times).

From this simulations it is evident that the reason that the current collection threshold is much larger early in time is that the sheath region is large. When the sheath region is large the electric field is not large enough so that the particle orbits have a minimum approach distance to the Langmuir probe so that they will be collected.

CONCLUSIONS

The temporal evolution of the current collection of a Langmuir probe inserted in the near-wake region of a conducting body has been studies in the laboratory with the aid of a pulsed plasma wind experiment. This experimental arrangement allowed the study of the dynamics of current collection without the influence of the vacuum chamber walls. Measurements of the temporal evolution of the current-voltage characteristic of a Langmuir probe in addition to direct probe measurements of the plasma potential during the formative process of the wake region were made. From these experiments it was determined that a threshold voltage exists for the collection of ions by a biased Langmuir probe in the wake region. This threshold voltage decreases as the sheath region around the probe is established and the electric field increases. No similar threshold voltage for the collection of electron current exists due to the small electron mass.

ACKNOWLEDGEMENTS

These experiments were supported by NASA under grant number NAGW 1572.

REFERENCES

1. Chan, C., Browning, J.,Meassick, S., Morgan, M., Cooke, D., Enloe, D., and Tautz, M., "Current Collection in a Spacecraft Wake; Laboratory and Computer Simulations", Proceedings of the Spacecraft Charging Technology Conference, Monterey, CA, 31 October-3 November, 1989.

2. Chan, C., Hershkowitz, N., Ferreira, A., Intrator, T., Nelson. B., and Lonngren, K., "Experimental ob-

servation of self similar plasma expansion", PHYS. FLUIDS. Vol. 2, 1984, pp. 266.

3. Dahl, D. A., and Delmor, J. E., "SIMION", EGG CS 7233 Rev. 2, EG+G Idaho Inc., Idaho Falls, April 1988.

4. Meassick, S., Chan, C. , Qian, Y., Sroda, T., Azar, T., and Allen, R., "Temporal Study of Wake Formation Behind a Conducting Body", J. GEOPHYS. RES., (Accepted for publication).

5. Medved, D. B., "Measurement of ion wakes and body effects with the Gemini/Agena satellite", RAREFIED GAS DYN., Vol. 1, 1969, pp. 1525.

6. Morgan, M. A., Chan, C. , Cooke, D. , and Tautz, M., "The dynamics of charged particles in the near wake of a very negatively charged body - laboratory experiment and numerical simulation", IEEE TRANS. PLASMA SCI., Vol. 17, 1989, pp. 220.

7. Morgan, M. A., Chan, C., and Allen, R., "A laboratory study of the electron temperature in the near wake of a conducting body", GEOPHYS. RES. LETT., Vol. 14, 1987, pp. 1170.

8. Murphy, G. B., D'Angelo, N., Kurth, W. S., and Pickett, J., "Measurement of plasma parameters in the vicinity of the space shuttle", PLANET. SPACE SCI., Vol. 34, 1986, pp. 993.

9. Raitt, W. J., Eccles, J. V., Thompson, D. C., Banks, P. M., Williamson, P. R., and Bush, R. I., "Plasma parameters in the near wake of the space shuttle", GEOPHYS. RES. LETT., Vol. 14, 1987, pp. 359.

10. Samir, U., Gordon, R. , Brace, L., and Theis, R., "The near wake structure of the atmospheric explorer C (AE C) satellite: A parametric investigation", J. GEOPHYS. RES., Vol. 84, 1979, pp. 513.

11. Samir, U., and Fontheim, E. G., "Comparison of theory and in situ observations for electron and ion distributions near the wake of the Explorer 31 and AE C satellites", PLANET. SPACE SCI., Vol. 29, 1981, pp. 975.

12. Samir, U., Wildman, P. J., Rich, F., Brinton, H. C., and Sagalyn, R. C., "About the parametric interplay between ionic mach number, body size, and satellite potential in determining the ion depletion in the wake of the S3 2 satellite", J. GEOPHYS. RES., Vol. 86, 1981, pp. 11 and 161.

13. Samir, U., Comfort, R. H., Chappell, C. R., and Stone, N., "Observations of low energy ions in the wake of a magnetospheric satellite", J. GEOPHYS. RES., Vol.91, 1986, pp. 5725.

14. Smith, J., Hershkowitz, N., and Coakley, P., "Inflection point method of interpreting emissive probe characteristics", REV. SCI. INSTRUM., Vol. 50, 1979, pp. 210.

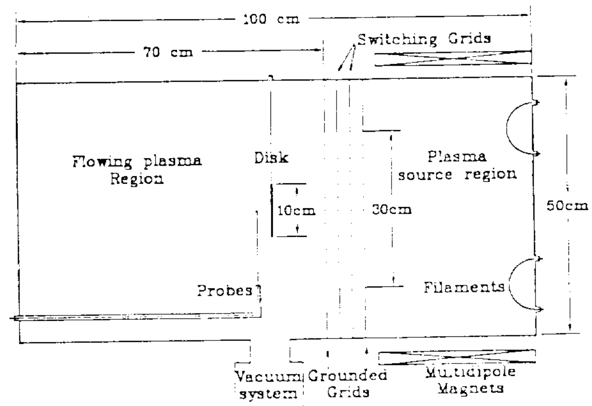

Figure 1: Schematic diagram of the Pulsed Plasma Wind Experiment (PPWE).

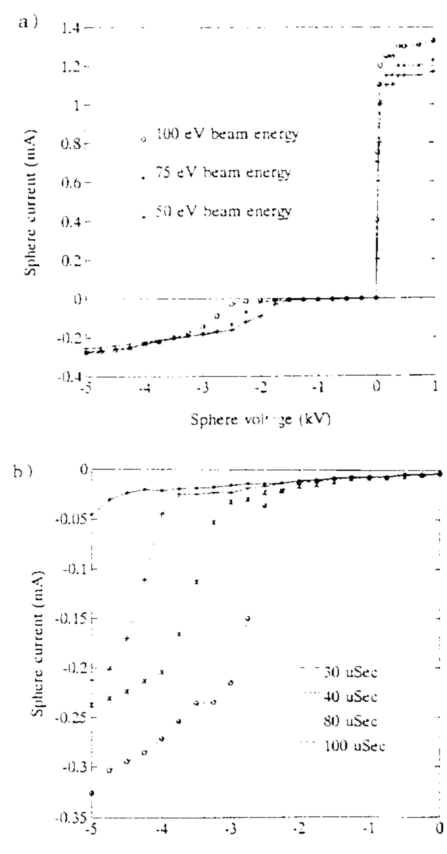

Figure 2: (a) The current-voltage characteristic of a Langmuir probe placed in the near wake region of a conducting sphere. The wake is created by a Mach=8 plasma flow. (b) The temporal evolution of the current-voltage characteristic of the Langmuir probe during the formation of the wake.

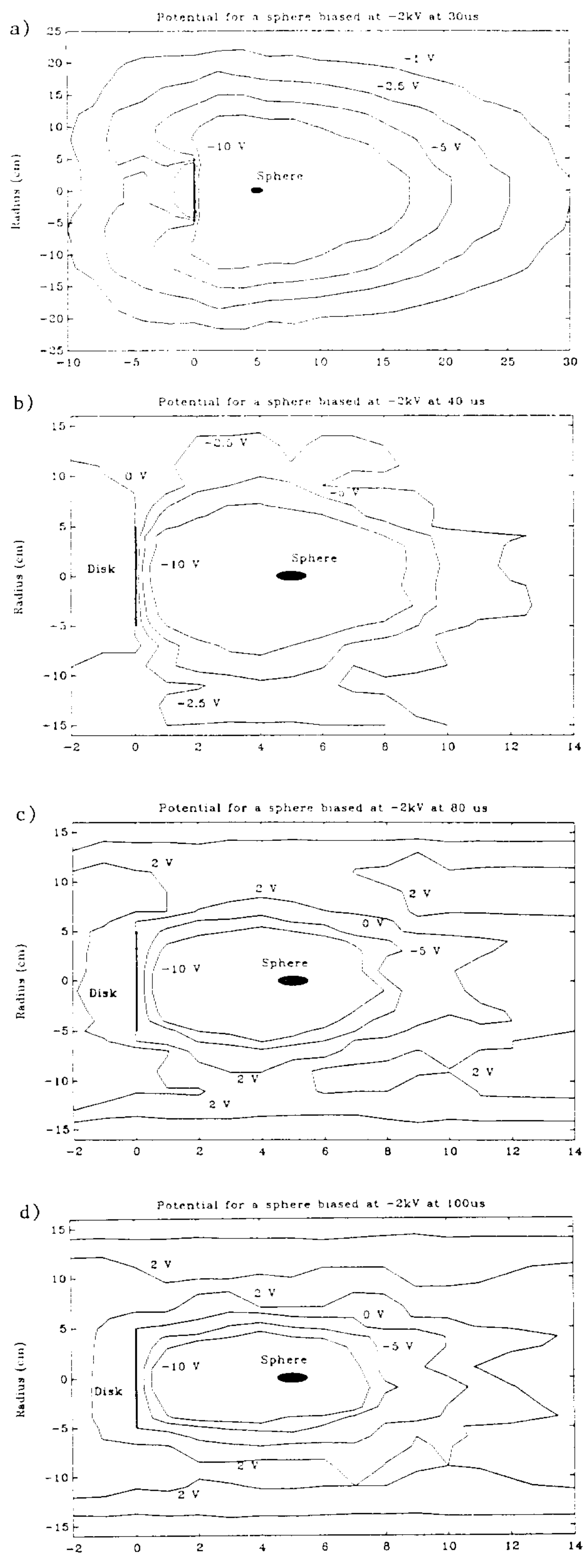

Figure 3: Plasma potential profiles around a Langmuir probe biased at -2000 V at (a) 30 μs, (b) 40 μs, (c) 80 μs, and (d) 100 μs.

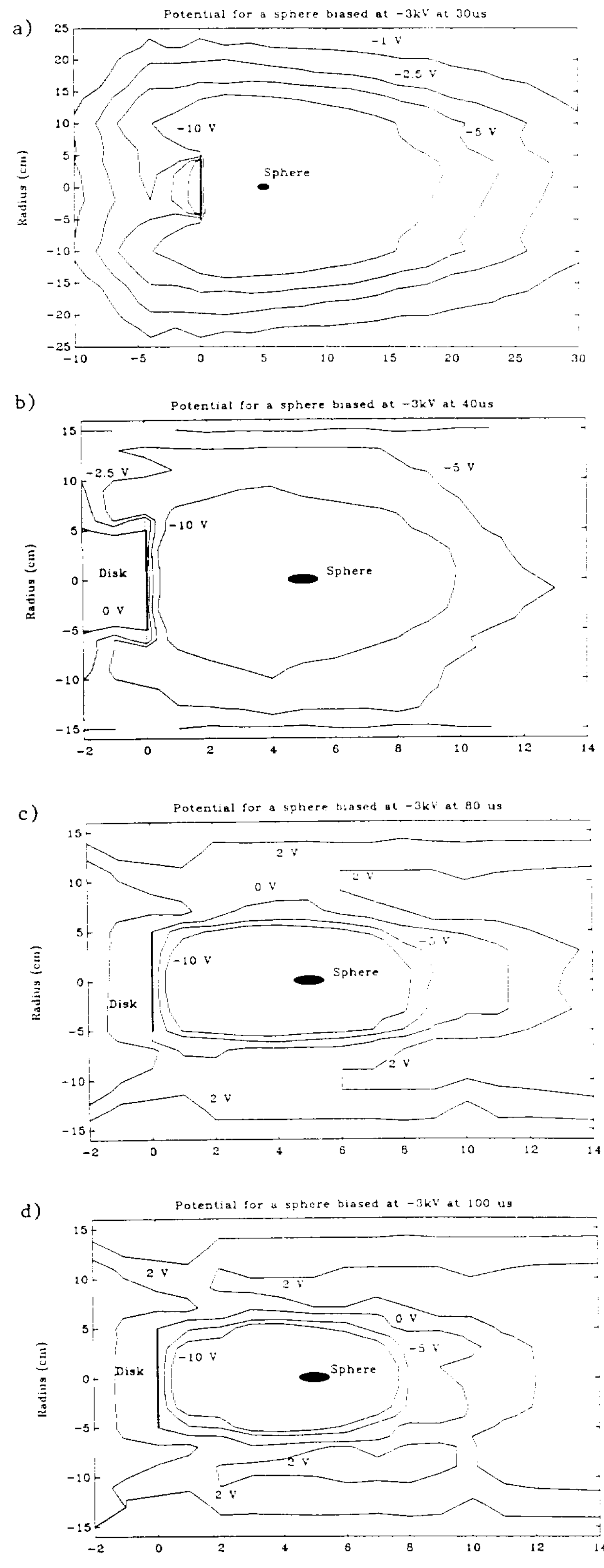

Figure 4: Plasma potential profiles around a Langmuir probe biased at -3000 V at (a) 30 μs, (b) 40 μs, (c) 80 μs, and (d) 100 μs.

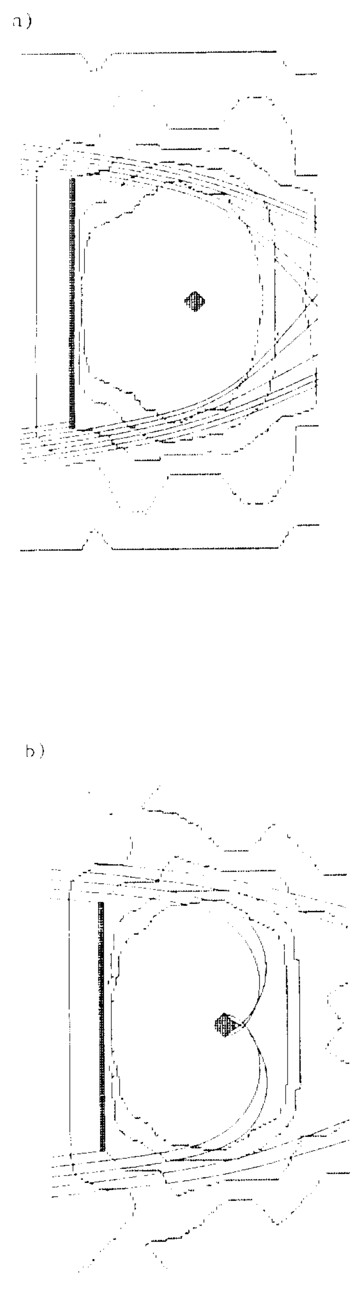

Figure 5: Ion trajectories predicted with SIMION for Langmuir probe bias potentials of (a) -2000 V and (b) -3000 V show that ions are only collected for -3000 V.

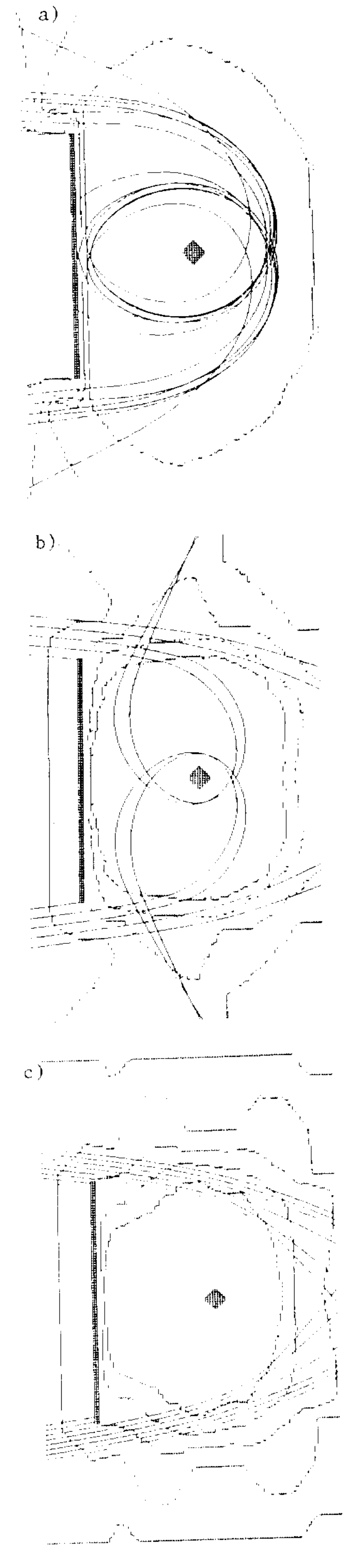

Figure 6: Ion trajectories predicted with SIMION for a Langmuir probe bias potential at -3000 V at (a) 40 μs, (b) 80 μs, and (c) 100 μs.